PULSED POWER TO THE AID OF CHEMICAL GUNS

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Abstract: The paper deals with the design and operation of an experimental set up consisting of a 6 cm bore gas cannon using standard propellant and a traveling-wave induction accelerator. The projectile consisting of an aluminum cylinder weighing 120 grams, is initially brought up to a speed of 600 m/s in the gas cannon. The pulsed-power stage is designed to accelerate the projectile further to a velocity of 700m/s.

INTRODUCTION

The muzzle velocity of conventional chemical guns is limited. On the other hand, pulsed power guns attain their best efficiency only in the high-speed range. This makes for an ideal two-stage combination in which the pulsed-power stage is positioned at the muzzle end of the chemical one.

CHEMICAL GUN SECTION

The Gun:

The gun is one of a series of thin walled 60mm research cannon designed specifically for vibration studies. Typically transverse motion of the tube wall has been measured for a variety of bore shapes, created by planned manufacturing variation and by various support modes. It is of interest to determine the response of these barrels to axial loads directed toward the breech. Thus, forming the experimental cannon from a gas gun with an EM accelerator at the muzzle provides an opportunity both to evaluate the barrel response to axial loads created by an EM accelerator or any other source, and to evaluate the response of the EM device to the harsh environment at the muzzle end of a gas cannon. This particularly includes transverse barrel whip, the through passage of a projectile that is already vibrating in multiple modes and the passage of erosive, hot, high pressure gas.

The Barrel:

The barrel is an extra long construction with a high expansion ratio i.e., total volume divided by chamber volume. This usually provides a very high efficiency expansion and higher than usual velocity for a given ratio of charge mass to projectile mass. The barrel is 60mm bore diameter and provides 3.5 meters of travel. Chamber volume is variable depending on the use of spacers, but in this case a volume of 9.5 cubic inches is provided behind the seated projectile. The chamber is 1/4 filled with 33 grams of propellant. This low charge imparts 600 m/s to the light weight projectile, but more importantly it provides a relatively (for cannon) low pressure, low erosive state to the propelling gas as it passes through the downbore EM device. Since the primary objective of this hybrid construction is to produce axial forces and not to develop EM accelerators, this gas condition allows us to avoid a very central problem in any hybrid accelerator; that is the fabrication of a bore liner which at once is transparent to rapidly varying magnetic fields, and yet impervious to high temperature erosive gases. In our case we only need to be magnetically transparent and be resistant to erosion for a few test rounds. Thus, a simple fiberglass/epoxy liner is used. As an aid to the survival of the liner, the barrel is supported so as to minimize bend and side thrusts between projectile and liner.

Muzzle End Test Device:

The muzzle end of the 60mm cannon was modified by adding a thread and pilot zone. See figure 1. This accepts a nut which is bore sized on the inner surface and threaded on the outer surface. The nut's inner surface is recessed to receive the bore liner. The nut's outer surface receives a large diameter

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14. ABSTRACT
The paper deals with the design and operation of an experimental set up consisting of a 6 em bore gas cannon using standard propellant and a traveling-wave induction accelerator. The projectile consisting of an aluminum cylinder weighing 120 grams, is initially brought up to a speed of 600 m/s in the gas cannon. The pulsed-power stage is designed to accelerate the projectile further to a velocity of 700m/s.

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split aluminum casing. Both the casing and the bore liner extend forward 18 inches to join to the muzzle end nut which serves to continue the bore and provide muzzle end closure to the EM device. Thus the annular volume enclosed axially between the end nuts, and radially between the liner and casing define a generalized test volume. Here a wide variety of EM devices may be tested. A linear induction launcher (LIL)[1] is installed, centered between three inch thick G10 axial standoffs from the steel nuts. Twelve Litz wire double layer pancake coils are fitted into 26.4cm between standoffs. Coax power cables are ported through the breech nut. Of the component joints, the threads joining the breech nut to the casing are the least robust and are sized for projectile to accelerator collision energy dissipation rate of 1.9 MJ per meter. Thus the 57KJ projectile of this test may be stopped in about a coil width without housing failure.

The availability of a modest capacitor bank dictated selection of various parameters which turned out harmoniously. At 15KV the three capacitor subgroups of 204 μF have available 69KJ. Initial circuit modeling showed that 8KJ of KE can be added to a projectile. A projectile entrance velocity into the LIL of 600 m/sec had been selected. Choosing a velocity increment of 100 m/sec, based on the limited available energy, meant that the projectile mass should be about 120g. This mass provides a 60 mm diameter aluminum cylindrical projectile with 2 calibers of wheelbase and a wall thickness of the order of a few millimeters. Impulse to the barrel is 12 Nsec at an average force of 30,000N.

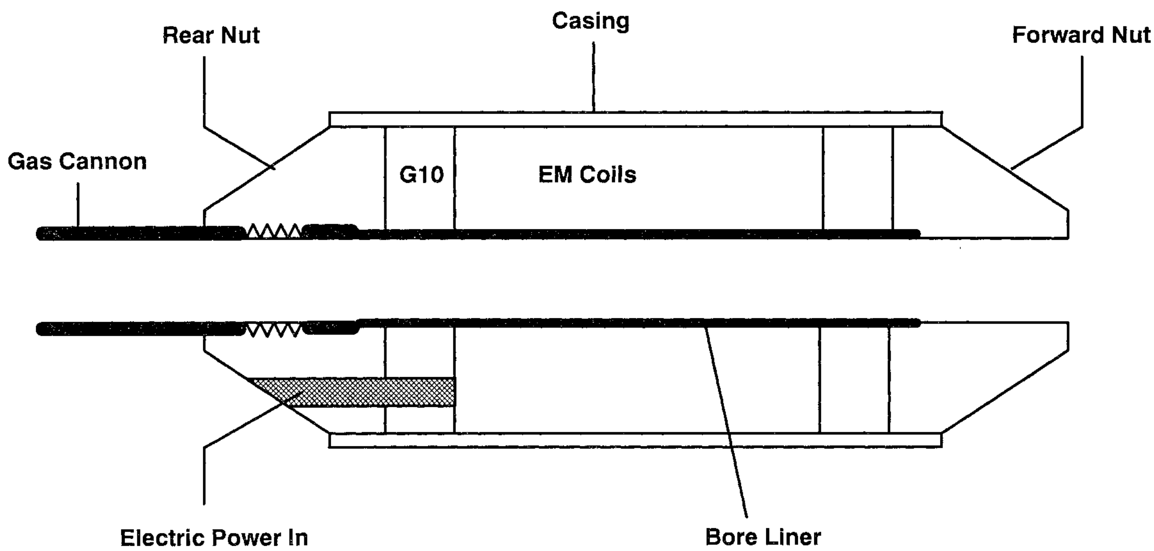

Fig. 1: Muzzle end EM device

The Projectile:

The projectile is designed for the peak acceleration required to meet the velocity goal. This in turn is based on the peak pressure. The first design concept had a cup shape with a thin wall and an integral base. However, analysis showed that even at the lowest expected gas pressure of 5000 psi, with uniform wall at skin depth thickness of 1.3mm, the base could only be 5mm thick within the 120g budget. The tension stress in the base plate was too high and the concept abandoned. In the new concept the base plate became a separable pusher plate, and the cylindrical wall became the singular EM driven entity with 120g mass budget allocated to it. The base plate could now be designed without material restraint, as added propellant would propel any necessary mass. Interior ballistic calculations showed that a fully burned charge would produce 17,000 psi in our 9.5 in^3 chamber and propel a combined mass of 234.5g to 600 m/sec. The 114.5g allocated to the pusher plate corresponded to a 15mm thickness. Finite element analysis indicated that pusher plate face tension dropped to the 15,000psi level. Cylinder wall thickness is 1.3mm at the leading edge. Rearward, the wall thickens exponentially to 3.83mm to hold the compressive contact stress at the cylinder/pusher plate junction at 34,000psi. Recent modeling shows a peak magnetic external pressure of 6300psi is expected. The skin depth-based thickness may be marginal to survive this load. However, charge establishment firings with slug(weight simulating) rounds and available propellant showed that 600m/sec could be attained with a peak pressure of 5000psi. Thus, the forward wall may be thickened to resist radial load.

Test Firing the Gas Gun:

After complete assembly of the EM device, with mass simulators replacing the coils, and O-rings sealing the ends of the bore liner, the two piece projectile is fitted in the bore. The pusher plate is provided with a breakable detent which prevents shot start until a selected pressure is reached. The pusher is further fitted with an O-ring seal to prevent propellant gas from separating the components prior to shot start. The leading edge of both components is cut with a suitable chamfer to ease traverse of bore interfaces. Doppler radar was used to measure velocity, a chamber pressure piezo gage was installed, and witness cards were set up at 8, 12, and 60 ft from the muzzle. General TV coverage of the range event was operating. Upon firing, velocity rose to 574m/s. The velocity trajectory is discerned from the Doppler radar data via time-frequency analysis[2]. This provides measurement of armature/projectile velocities during both the interior and exterior ballistic launch cycle. It is anticipated that armature separation from the pusher-plate will be readily discriminated. Figure 2 indicates the capability to resolve velocity, even when subjected to signal attenuation due to the witness cards. Piezo data was lost. Witness cards showed the circularity of the cylinder was retained and no buckling occurred. Recovery of large pieces of the cylinder showed unmarked leading edges, indicating very smooth entry into the fiberglass bore liner and the following muzzle nut. The bore liner showed no lifting or fiber separation at interface edges. No effects of heat transfer and erosion were observable within the bore liner. Particularly, initial pits or voids between fibers caused by poor resin fill did not grow or melt despite enhanced heat transfer at pit edges. This indicates that the liner will withstand higher pressure and velocity firings.

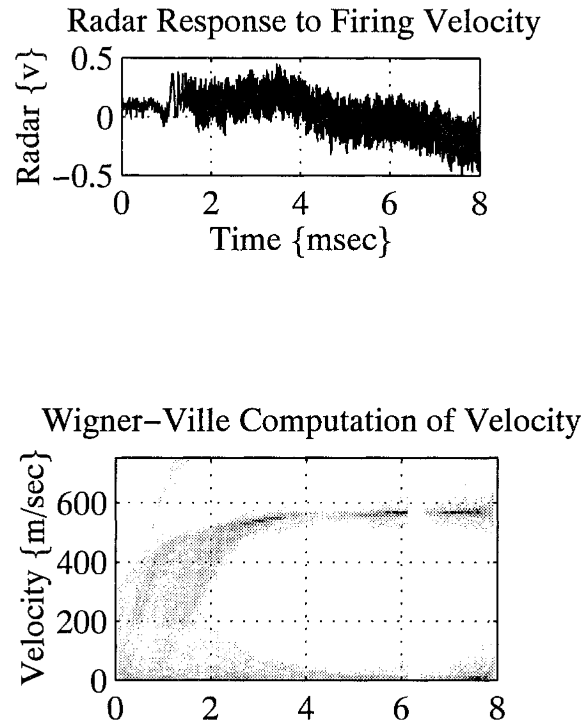

Fig 2: Velocity Determination.

ELECTROMAGNETIC LAUNCH SECTION

This part of the paper describes the coilgun section. It includes the design procedure, proposed dimensions, and predictions of its performance.

Principles of Operation:

The electromagnetic launch section consists of a coaxial coilgun called the linear induction launcher. The barrel consists of a linear array of coils, energized by multi-phase excitation. The currents in these coils generate a magnetic traveling-wave energy packet. In turn, this induces currents in a conducting cylinder (sleeve) which houses the projectile. The interaction of these currents produces strong propulsion and centering forces.

The sketch of Fig. 3 suggests more clearly how the launcher is constructed, and the mechanism by which the projectile is propelled. Currents in the drive coils, indicated by large arrows, establish a magnetic field, represented by the outer set of N - S poles, which moves to the right at a speed proportional to the frequency of the current oscillations. These currents induce a second set of currents (smaller arrows) in the sleeve, which, in turn, establish an inner set of N - S poles. This set of projectile current-generated poles is displaced a short distance to the right of the set of barrel poles. Since like magnetic poles repel, and unlike poles attract, the projectile moves to the right. In addition, inward directed forces 'levitate', or center, the projectile within the barrel.

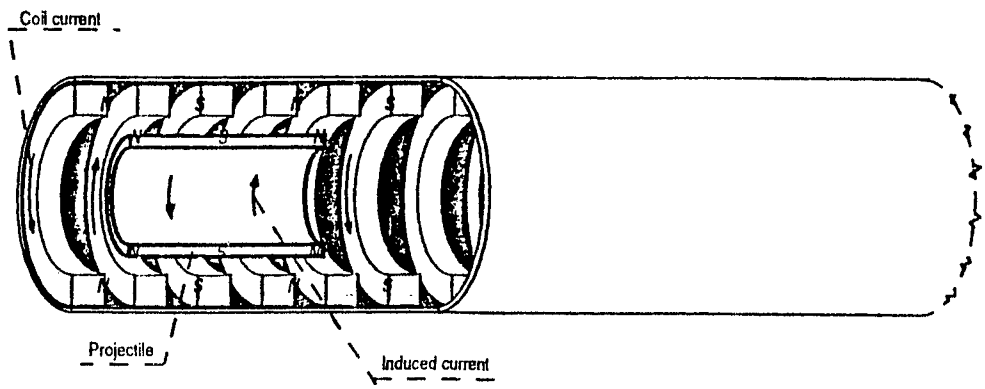

Fig. 3: Construction of the linear induction launcher (LIL)

Specifications and Constraints:

The electric stage of the hybrid gun is required to increase the velocity of the projectile from 600 to 700m/s, subject to the following constraints:

Power supply: only 12 capacitors, 22 kV, 51 μF and three ignitron switches were available.
Coilgun Barrel: 6 cm inner diameter. 26.4 cm long, mounted at the muzzle end of the gun.
Projectile: a hollow aluminum cylinder weighing 120 grams.

The dynamic resistance of the capacitors and of the switches has not yet been measured. Since the total resistance determines the rate of decay of the current in the barrel coils, it is not possible at this time to make very accurate predictions of the muzzle velocity. In the future, consideration will be given to the use of a flywheel motor/generator set in place of the capacitor bank, in order to reduce the bulk and weight of the power supply.

Design Procedure:

With three-phase energization, once the number of coils has been prescribed, the pole pitch is uniquely determined. Assuming values for the muzzle velocity and for the slip of the projectile behind the electromagnetic wave traveling down the barrel, the supply frequency is also uniquely determined. From the value of the capacitance and circuit resistance, resonance with the barrel coils determines the values of their inductances, and therefore, the number of turns. It is noted that, in this case, the unknown dynamic resistance of the capacitor and of the switches constitutes the dominant part of the total circuit resistance and, hence, is a source of uncertainty. It is also noted that the number of coils, 12, represents four pole pitches and allows some flexibility with their parallel or series connection. The assumption of the enhanced muzzle velocity, in this case 700 m/s, determines the final kinetic energy of the projectile and, hence, the average electromagnetic force acting on it. Using formulas previously derived and validated [3] for a steady-state condition, it becomes possible to predict the coil currents and voltages.

Design Specifications:

The procedure outlined above leads to the following dimensions and data:

Coils: Double pancake coils, each with a total of 6 turns (3 turns in each half-coil), 6 cm inner diameter, 6 mm height, and 2 cm width, 60 kA peak current and 7.5 kV peak voltage. The connections for phase A are shown in Fig. 4

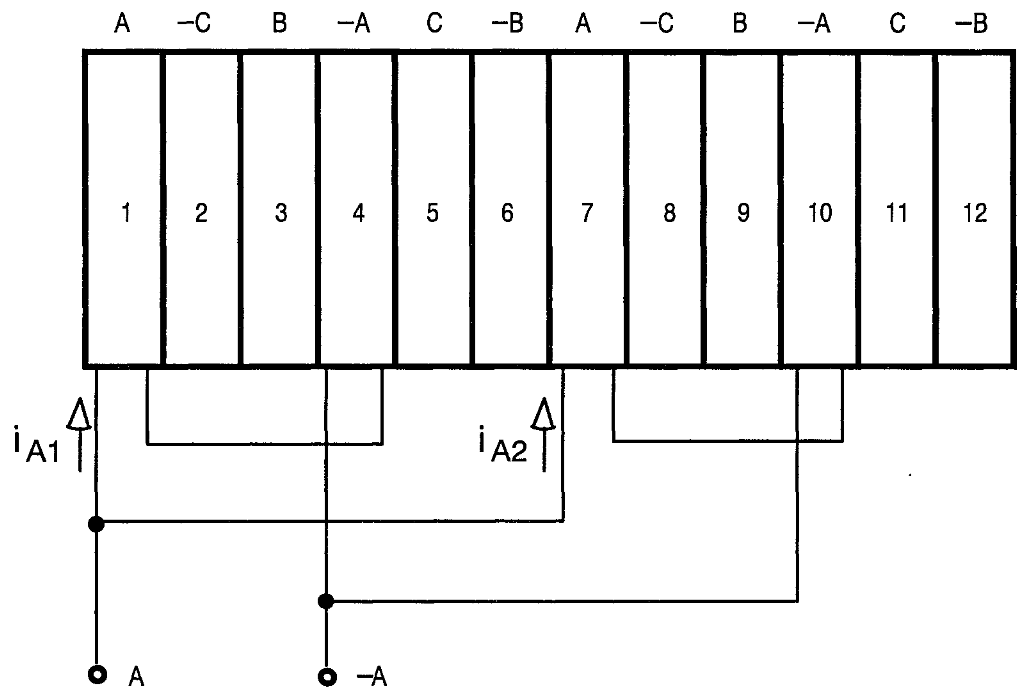

Fig. 4: Terminal connection of one phase of the LIL section

The series/parallel connection was dictated by the value of the available capacitors. A finite element method FEM was used to evaluate mechanical forces. Each coil is subjected to a peak longitudinal stress of 3,150 lb/in2 and a peak radial stress of 6,300 lb/in2.

Projectile: The projectile consists of two separate parts: an aluminum sleeve, as shown in Fig. 5, backed by a fiberglass/epoxy disk that sustains the gas pressure.

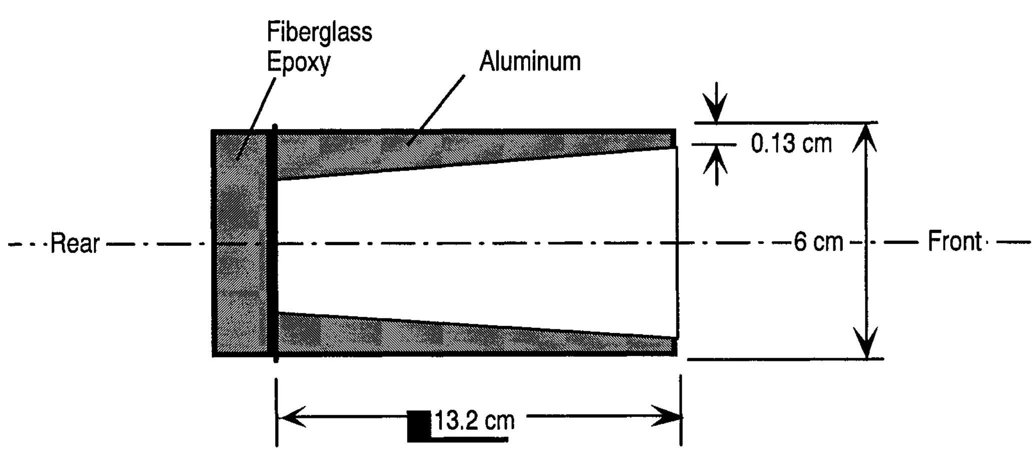

Fig. 5: The two parts of the experimental projectile

In the electric section of the gun, the LIL section, the aluminum sleeve (but not the disk) is given an additional acceleration, leaving the fiberglass/epoxy disk behind.

Predicted Results:

To predict the LIL section performance, a previously developed mesh-matrix code [4} was used. Each drive coil is represented as a lumped R-L-C circuit. The projectile is assumed to be segmented into 20 coaxial rings, and each is represented by an R-L lumped circuit. The mutual inductances among all of the drive and projectile coils are re-calculated during each iteration (i.e., each incremental movement of the projectile). The code provides results for the voltage and current of each coil of each phase; the position of the projectile; temperature rise in both the drive and projectile coils; projectile velocity; acceleration; and mechanical forces acting on the projectile. It also allows the system parameters to be optimized.

By inter-connecting the capacitors to form a bank of 204 μF per phase, the required input frequency becomes 6,333 Hz. The synchronous velocity of the traveling magnetic wave is $V_S = 2\tau \cdot f = 2 \cdot 0.066 \cdot 6333 = 836$ m/sec. The first phase of the LIL is triggered when the relative position of the rear of the incoming aluminum projectile with respect to the entry plane of the coilgun section is -11 mm. The negative sign indicates the 13.2-cm-long projectile is almost completely inside the coilgun section. The other two phases are self-triggered 60° later, 60° apart. For an initial voltage of 13.5kV per capacitor per phase, and assuming $r = 0.01\Omega$ for the per phase combined resistance of the capacitor bank, ignitron switch and circuit cable wiring, the computer code predicts the following results:

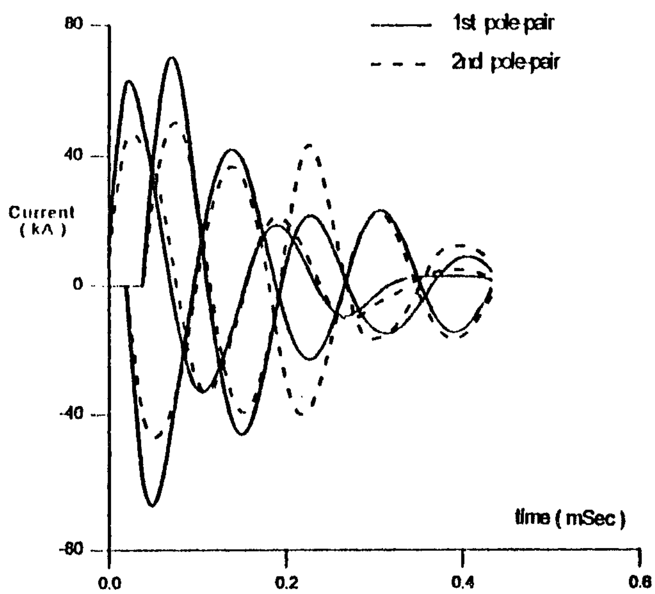

Fig. 6: Currents in the two parallel parts of the LIL

Fig. 6 shows the three-phase drive-circuit currents. The amplitude difference between the current in the first pole-pair (i_{A1} in Fig. 4) and the second pole-pair (i_{A2} in Fig. 4) is caused by the effect of the mutual inductances between the projectile and the corresponding section of the barrel.

The fluctuation in the force curve (Fig. 7) is a result of the relative position between the traveling waves of both the barrel and projectile. The negative part, at the beginning of the force-curve, is generated when the first of the three phases is energized, i.e., before the traveling wave has been established. Those fluctuations affect the velocity profile (Fig. 8). The projectile enters the barrel at 600 m/sec and leaves at 700 m/sec. The transit time is 0.44 msec, at an average acceleration of 23,000 gee's.

A rotating machine such as a synchronous generator (flywheel motor/generator set) may be used to replace the capacitor bank. This would serve to reduce the volume and weight of the pulsed power source. Also, this would permit the LIL section to be energized prior to the arrival of the projectile at the LIL. By that means, it will accelerate the projectile as soon as it arrives in the LIL section, without the need for a special synchronizing switch.

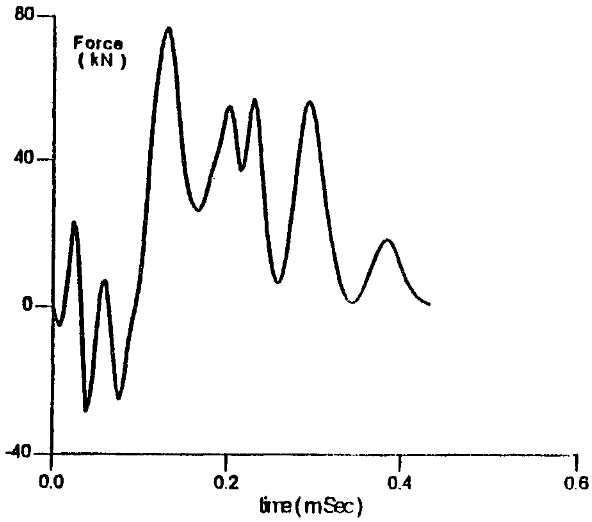

Fig. 7: Longitudinal force vs time

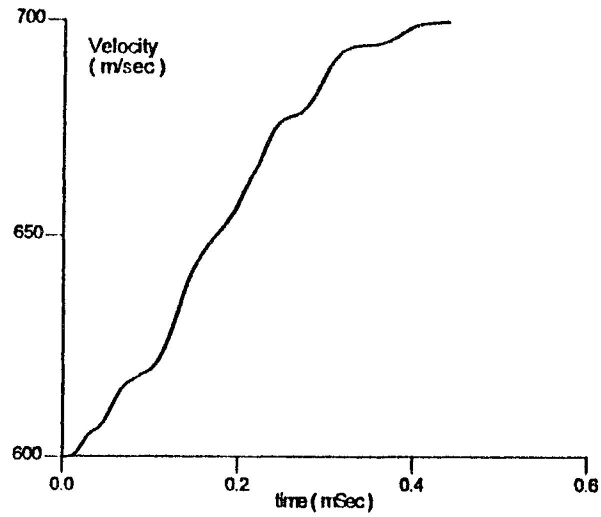

Fig. 8: Projectile velocity vs time

CONCLUDING REMARKS

The paper has presented a hybrid concept: a chemical/electromagnetic gun in which the EM coil part is attached as an extension to the muzzle end of the conventional gun. Design specifications, initial tests, and computer code predictions have been described. The constraints imposed on the power supply and on the design are expected to adversely affect the performance of the present hybrid gun. Nevertheless, much will be learned about the potential of this new concept. The system is now under construction at the U.S. Army Benét Laboratories. The actual experimental results will provide a learning tool for scaling up and optimization. The LIL is the only electromagnetic launcher that can operate using an alternating-current-energization system. Therefore, it is possible to use a flywheel motor/generator set, instead of the capacitor bank. This, it is anticipated, will greatly reduce the volume and weight of the pulsed power supply.

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